combine factors that create a favorable environment for the active formation of mudflows. Here there is a steep mountain relief in the upper reaches, sedimentary and metamorphic rocks that are unstable to landslides, intense atmospheric influence, a dense hydrographic network, and specific features of the soil and vegetation cover. To conduct the study, 5 statistical series of characteristics of mudflows were formed - areas of mudflow basins, elevations of their highest points, lengths and average slopes of mudflow channels, elevations of their closing sections. The total number of members of the above-mentioned series according to each of the characteristics of mudflows is 143 (125 in the Prut river basin, 18 in the Siret river basin). The source data bank was created based on many years of data from expeditionary work of the Ukrainian Hydro meteorological Institute and the hydrographic party of the Borys Sreznevsky Central Geophysical Observatory, information on the consequences of the passage of mudflows collected in road and forestry organizations. The main methods used are methods of mathematical statistics, namely, histograms of the distribution of characteristics of mudflows and correlation-regression analysis of the relationships between them were used. The constructed histograms of relative frequencies in the form of partial intervals for all the studied characteristics demonstrated the peculiarities of their distribution, which made it possible to identify the most typical indicators of mudflows inherent in the studied territory. Correlation-regression analysis showed the interdependence and interrelationship between the studied characteristics of mudflows. The results obtained are of practical importance, as they characterize the main patterns and features of the formation of mudflows in the Prut and Siret river basins, which are dangerous hydrological phenomena in the mountainous and foothill parts of the studied territory.

Keywords: *mudflows, Prut and Siret river basins within Ukraine, statistical analysis, mudflow characteristics.*

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HYDROGRAPHIC NETWORK TRANSFORMATIONS IN POSTGLACIAL AREAS – A CASE STUDY OF THE KRAJEŃSKI LANDSCAPE PARK

The article presents a study on the transformation of hydrographic networks within protected areas. The research is based on the analysis of cartographic materials using GIS software. The temporal scope of the study covers the 19th and 20th centuries — a period marked by the most significant alterations to hydrographic systems due to human activity. The research was conducted within the Krajeński Landscape Park, one of the largest protected areas in the North Polish Lowlands. The results indicate a decrease in the lake surface area and a slight increase in the length of rivers (artificial canals). The primary causes of these changes are attributed directly to human activity, particularly land drainage for agricultural purposes (drainage ditches), and indirectly to the increased eutrophication of waters. The study highlights the sensitivity of young glacial river–lake systems to anthropogenic pressures.

Protected areas represent an exceptionally unique part of the natural environment that requires sustainable management aimed at preserving their value for future generations. However, due to human activity and climate change, these areas are increasingly subject to various pressures, including transformations of the hydrographic network. The study aimed to assess the hydrographic network transformation using the example of the Krajeński Landscape Park (northern Poland).

Due to the lakeland character of the study area, it constitutes an environment highly sensitive to any changes in water management. The analyses conducted using GIS tools made it possible to identify the main directions of hydrographic network transformation over the past centuries, revealing a strong impact of human activity. A decrease in lake surface area was observed, accompanied by an increase in the length of rivers and drainage ditches. This trend reflects the intensive meliorations carried out in the area in the past, anthropogenic modifications of riverbeds, and the acceleration of eutrophication processes in lakes and wetlands resulting from changes in the entire hydrographic network.

The study highlights the need for sustainable management of the landscape park to protect habitats and water-related areas.

Keywords: *hydrographic network, rivers, lakes, wetlands, GIS, protected areas, Krajeński Landscape Park.*

INTRODUCTION

The hydrographic network transformations in postglacial areas refer to the alterations and dynamics of water systems that emerge in regions previously affected by glacial activity. These transformations are significant due to their profound implications for both ecological state and landscape management, particularly within landscape parks. Postglacial landscapes are characterized by features such as lakes, wetlands, and lower-order streams that reflect the complex interplay between sediment deposition, erosion, and hydrological processes resulting

from glacial retreat (Bajkiewicz-Grabowska et al., 2020). Understanding these networks is critical for managing biodiversity and ecosystem services in regions impacted by changing climatic and anthropogenic influences.

In postglacial areas, the hydrographic networks have experienced substantial changes over the past due to both natural phenomena and human activity. The significance of these transformations lies in their capacity to affect water availability, habitat connectivity, and biodiversity, prompting ongoing inquiries into sustainable management practices that can mitigate adverse impacts and promote ecological resilience in these sensitive environments (Lai, Anders, 2018). The hydrographic networks in postglacial areas exhibit distinct characteristics that are primarily influenced by the remnants of glacial activity. These networks typically consist of lakes, wetland regions, and various watercourses, predominantly characterized by lower-order channels in the Strahler classification. These channels are often short, periodic, and function as overflows, utilizing valleys that were shaped by the melting of glaciers and the resulting hydrological processes (Bajkiewicz-Grabowska et al., 2020).

The main components of these hydrographic networks include lakes, which can vary significantly in size, and boggy areas that retain moisture, forming unique ecological niches. Additionally, watercourses in these regions are essential for channeling meltwater and rainwater, contributing to the overall hydrological dynamics. The interplay between these elements creates a complex system that supports a diverse array of flora and fauna, often adapted to the specific conditions of postglacial environments.

The hydrographic networks in postglacial areas have undergone significant transformations. These changes have resulted from both natural processes and anthropogenic influences, leading to alterations in drainage patterns and water availability. Research indicates that the density and distribution of watercourses can vary greatly, influenced by local topography and climatic factors. For example, dendritic drainage patterns are often observed in higher elevation areas, while more sub-parallel configurations may be found in lower, more transient zones. These transformations are critical for understanding how ecosystems adapt to changing hydrological conditions and can have lasting impacts on biodiversity and land use in postglacial regions. The study of these networks thus provides insights into broader environmental changes and assists in the management of natural resources within landscape parks and similar areas (Góraj et al., 2017; Stachowicz et al., 2024).

In Poland, the Biebrza National Park area has experienced significant landscape transformations, including alterations to its hydrographic networks, particularly from the 19th to the 21st century (Stachowicz et al., 2024). Research focusing on the Biebrza wetlands has shown that these transformations have resulted from various factors, including human activity and environmental changes. Investigations conducted between 1999 and 2002 aimed to understand flooding phenomena within the valley and their relationship with vegetation patterns. It was found that the inundation of the valley was influenced not only by river water but also by groundwater seepage and snowmelt, indicating a complex interplay of hydrological processes.

Controversies surrounding hydrographic transformations primarily focused on the balance between development and conservation. As urbanization expands into postglacial landscapes, the challenge of integrating recreational spaces with ecological preservation becomes increasingly prominent. Effective strategies must address water management while recognizing the ecological integrity of these landscapes to prevent biodiversity loss and habitat fragmentation. These dilemmas highlight the need for collaborative efforts among scientists, policymakers, and local communities to navigate the complexities of managing hydrographic networks in a changing world (Ralston, Sarr, 2017).

Hydrographic changes induced by human activity have led to significant alterations in the habitats and ecological conditions of various species within affected ecosystems. Such transformations often result in habitat fragmentation and modifications in vegetation structure and food resources, ultimately impacting species diversity and richness across different taxa. The changes to hydrographic networks have also affected the broader ecological dynamics within these landscapes. A study noted that significant reductions in lake area led to noticeable shifts in species quantity and distribution, further complicating the ecological interactions among resident species.

The main objective of the research was to identify the transformations of the hydrographic network in a postglacial area, using as an example the protected area of the Krajeński Landscape Park. Archival and current cartographic materials were used for spatial analyses. The research identified the changes and assessed their impact on the condition of protected areas, such as the Krajeński Landscape Park.

STUDY AREA

Krajeński Landscape Park is among the largest landscape parks in Poland and is the largest landscape park in the Kuyavian-Pomeranian Voivodeship. The study area is the Krajeński Landscape Park, established in 1998. It covers a total area of 73,850 hectares and includes rural areas of six municipalities: Więcbork, Sępólno Krajeńskie, Kamień Krajeński, Sośno, Mrocza, and Kęsowo, located in the Kuyavian-Pomeranian Voivodeship (in the northern part of Poland) - Figure 1.

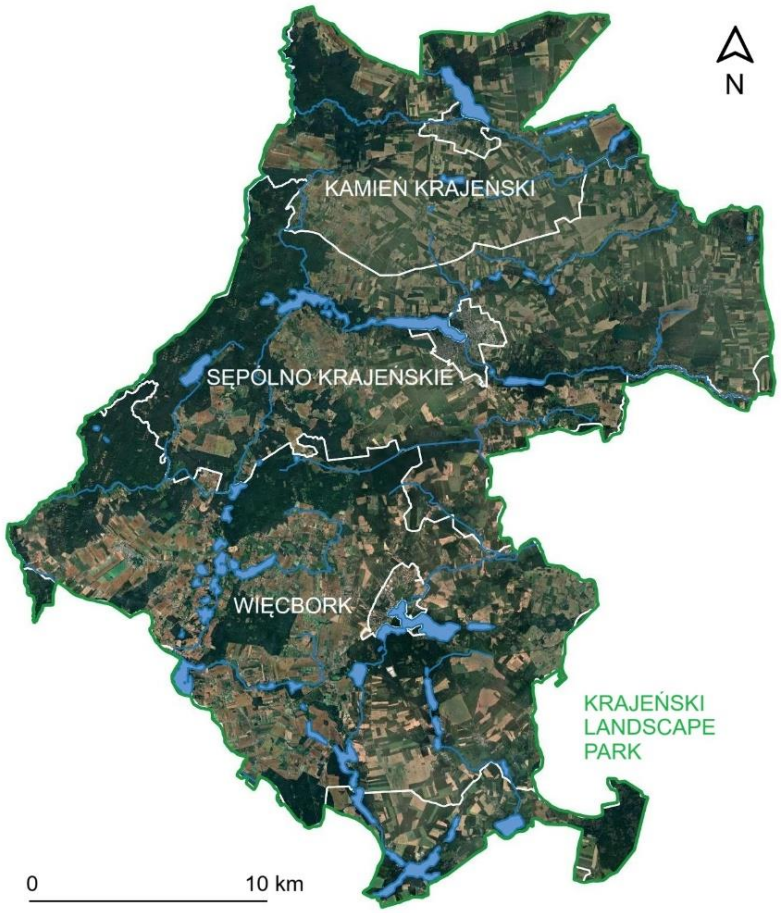

Fig. 1. **Study area of the Krajeński Landscape Park**

In terms of the physical and geographical division of Poland, the study area is located at the Krajna Landlake mesoregion (Kondracki, 1977). In the Quaternary, the area of today's Krajeński Landscape Park was a watershed, which is why the river network was poorly developed here in the interglacial periods. The current area of the Park is composed mainly of clays, as well as clayey sands. Smaller areas are occupied by outwash sands and organic material (Pasierbski, 2003). Approximately 2,800 hectares of water bodies have been identified within the Krajeński Landscape Park. In the internal structure of a landscape park, flowing waters, such as rivers, streams, and river-lake systems, are dominant, accounting for 79.3% of the total area in this category (Rudnicki, 2008). The most important rivers of the Krajeński Landscape Park are the Kamionka and Sępolenka, belonging to the Vistula river basin, and the Orla, Rokitka, and Lubcza, belonging to the Odra river basin. An important element of the landscape of Krajeński Landscape Park is the lakes, which are about 100 of them in the study area. The largest lakes included: Więcborskie (approx. 200 ha), Sępolnońskie (159 ha), Lutowskie (156 ha), Mochel (153 ha),

Stryjewo (151 ha), and Witosławskie (107 ha). There are many wetlands in the Krajeński Landscape Park, the vast majority of which are small wetlands with an area of less than 1 ha, belonging to the seasonal type.

MATERIALS AND METHODS

Hydrographic surveying is a fundamental methodology used to evaluate changes in hydrographic networks, particularly in postglacial landscapes. This discipline employs various techniques to collect hydrological data essential for understanding and managing water resources (Klemas, 2011). Key tools include satellite data (e.g., LIDAR, etc.), and field surveys (e.g., using drones). Remote sensing technologies and Geographic Information Systems (GIS) play a pivotal role in studying hydrographic transformations. Satellite imagery and aerial surveys allow researchers to observe large-scale changes in land cover and hydrological patterns over time. These tools facilitate the mapping of hydrographic features, providing a comprehensive overview of how landscape transformations affect the hydrographic network. The integration of computational models further enhances data analysis and interpretation, allowing hydrologists to simulate water dynamics in different ecosystems.

Input data of the study were open-source archival topographic maps (from German: Meßtischblätter) from the beginning of the XX Century (mapy.amzp.pl), and an open-source actual watercourses map based on the Hydrographic Map of Poland from the beginning of the XXI Century (geoportal.gov.pl).

Georeferencing of historical maps is a key step that enables the comparison of cartographic data from different periods. This process involves assigning spatial coordinates in a specific reference system — most commonly PUWG 1992, which is the standard in Polish GIS analyses — to raster scans of maps.

In the case of studies on the hydrographic network of the Krajeński Landscape Park, it is necessary to maintain high georeferencing accuracy, especially in the areas of watercourses and catchment boundaries. Control points are used for georeferencing — distinct terrain features (road intersections, bridges, forest edges, elevation points) that appear on both the historical and contemporary maps. Once spatial alignment is achieved, manual digitization follows, i.e., the vectorization of hydrographic network elements such as rivers, streams, lakes, and others. This process is carried out in GIS software (Quantum GIS 3.22.6) by creating linear and polygonal layers. Additional information, such as the names of watercourses, their classification, calculated areas, etc., was also created in QGIS tools.

RESULTS & DISCUSSION

The research showed significant changes in the hydrographic network of the Krajeński Landscape Park. In particular, a reduction in lake surface area (L) by 345.61 hectares was observed (Table 1). The total length of the river network increased by approximately 47 kilometers, although this may be attributed to differences in the classification of watercourses across various cartographic sources. The most noticeable change is the increase in the length of the drainage ditches (Table 1).

Table 1. **Changes in the Krajeński Landscape Park in the XX and XXI Century**

Year	Lakes (L) area [in ha]	River system length (R) [in km]	Drainage ditches length (D) [in km]	Total length R and D [in km]
1921	2,279.80	211.72	322.86	534.58
2023	1,934.19	258.92	705.89	964.81

The spatial distribution of changes in the hydrographic network is presented in Figure 2. A noticeable trend of decreasing lake surface areas is evident within the territory of the Krajeński Landscape Park, particularly in its southern part. This is especially visible in lakes Wiele and Pęperskie (Figure 2). The reduction in lake area is primarily caused by lake overgrowth (eutrophication), a process most prominent in the southern section of the Krajeński Landscape Park.

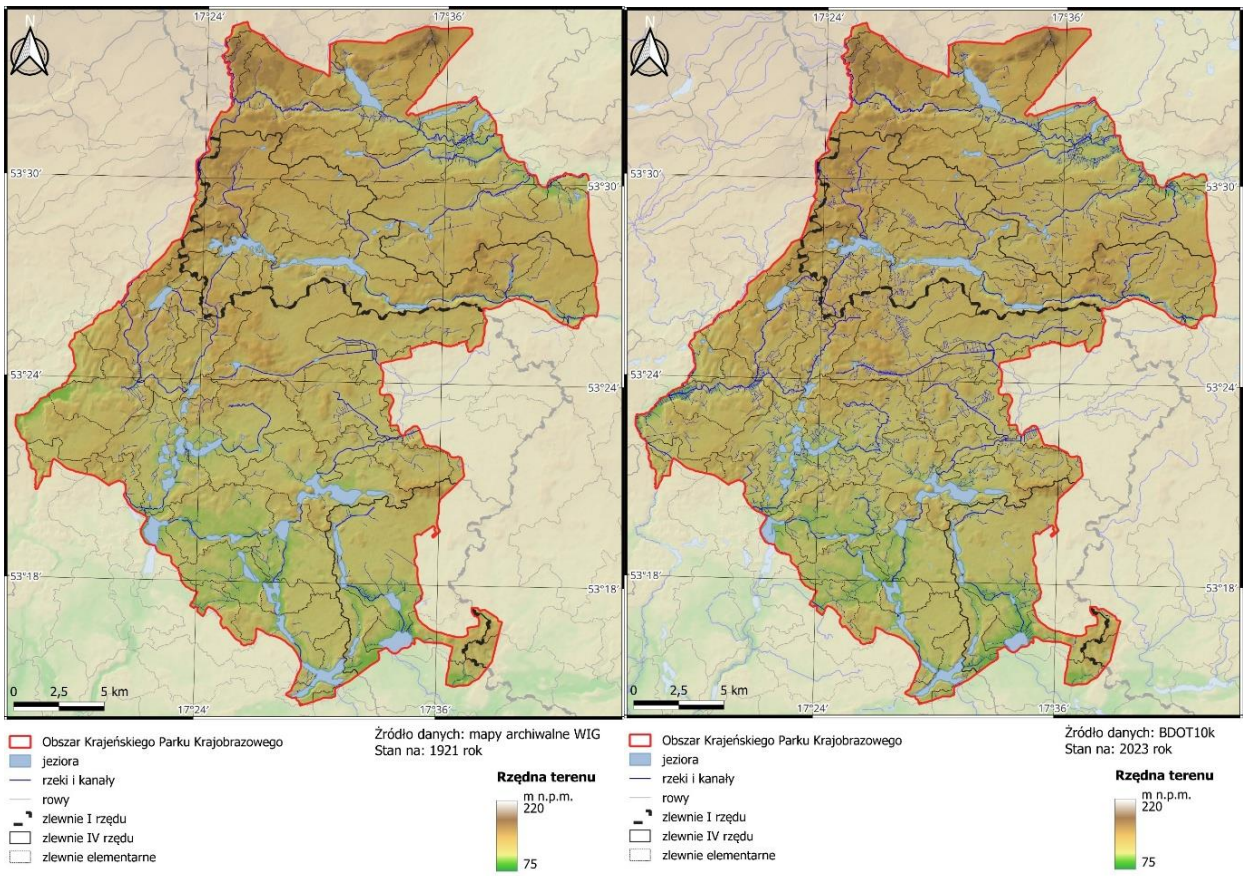

Fig. 2. **Changes in the river network of Krajeński Landscape Park area in the XX (A) and XXI (B) centuries**

In the Krajeński Landscape Park, a clear tendency of gradual lake surface reduction can be observed. This trend is one of the key indicators of the transformation of the region's hydrographic network. The phenomenon is both natural and anthropogenic, with the greatest intensity occurring in small mid-field ponds and lakes located within agriculturally intensively used catchments. The process is associated with deteriorating lake recharge conditions, accelerated eutrophication, and climate change affecting the overall water balance of the region.

One of the main causes of decreasing lake surface area is the reduction in surface and groundwater inflow. Lakes in the Krajna region are predominantly fed by groundwater and local streams with seasonal flow. Past drainage activities and hydrological modifications within catchments have increased surface runoff and reduced natural retention, leading to lower groundwater levels and a drop in lake water levels. In many cases, the streams supplying water to lakes have been partially filled in, shortened, or converted into artificial channels, significantly worsening the hydrological conditions of the lakes.

Agricultural activity conducted near lakes plays a significant role in accelerating this process. Excessive fertilization and a lack of proper buffer zones contribute to increased nutrient runoff, leading to the eutrophication of water bodies. As a result, there is intense overgrowth of littoral zones, expansion of reed beds, and accumulation of organic material in the form of bottom sediments, which systematically reduce both the volume and surface area of the lakes. At the same time, excess nutrients in the water cause algal blooms, reduced transparency, and oxygen depletion, all of which impair the functioning of lakes as full aquatic ecosystems.

Climate change, including increasingly frequent and prolonged dry periods, rising air temperatures, and higher evaporation rates, further intensifies the problem. As a result of a negative summer water balance, there is a noticeable recession of lake shorelines, the formation of marshy or silted zones, and a local decline in water levels. These trends are particularly evident in shallow, endorheic (closed-basin) lakes, with small surface areas and poorly developed inflow

systems. In extreme cases, such reservoirs may completely disappear, causing irreversible changes in the structure of local aquatic ecosystems.

Comparative analyses of cartographic data (topographic maps and orthophotos from various periods) confirm that many lakes within the Park have undergone a marked reduction in surface area in recent decades. For example, Lake Runowskie shows signs of severe overgrowth and shallowing in its southern part, while Lake Więcborskie exhibits a reduction of bays and the expansion of reed vegetation along its shores. In the case of smaller, unnamed ponds and mid-field reservoirs, the changes are even more drastic—many of them have been almost completely transformed into wet meadows, peatlands, or developed areas.

The shrinking of lake surfaces also has negative ecological and landscape consequences. It leads to: the loss of wetland habitats, a decline in biological diversity (especially waterfowl, fish, amphibians, and invertebrates), deterioration in the quality of surface waters, reduced retention potential and drought mitigation capacity of the landscape, and a decline in the recreational and tourism values of the Krajeński Landscape Park.

This phenomenon highlights the urgent need for monitoring the condition of lakes and implementing remedial actions, such as reducing surface runoff, creating buffer zones, restoring natural watercourses, and enhancing natural water retention. Maintaining water bodies in good ecological condition is crucial for preserving the hydrological balance of the young glacial landscape that characterizes the Krajeński Landscape Park.

Changes in the hydrographic network are primarily the result of the implementation and maintenance of drainage (melioration) systems. The drainage of wetlands leads to a lowering of the groundwater table over large areas. Moreover, water from drained wetlands and peatlands contains significant amounts of carbon and organic matter, which greatly accelerates lake eutrophication.

Melioration, understood as the set of activities aimed at improving water conditions in agricultural and forested areas by removing excess surface and groundwater, has played a key role in shaping the current hydrographic network of the Krajeński Landscape Park. These processes intensified particularly during the post-war period, in the 1950s to 1980s, when large-scale drainage programs were implemented throughout Poland to increase agricultural productivity by draining wetlands and improving land usability.

During the post II WW period, driven by centrally planned agricultural and industrial development, a systematic regulation of many watercourses, drainage ditches, and canals was carried out within the Park and its surrounding areas. The main objectives of these interventions were: to lower the groundwater level, enabling the cultivation of previously unused or inaccessible land, to improve drainage and remove excess rain and meltwater, to reduce the risk of local flooding, and expand the area of arable land.

In the Krajeński Landscape Park, drainage of peatlands and wetlands-characterized by naturally high groundwater levels and slow surface runoff-was particularly intensive. One notable example is the Messa region. In addition to Messa, other drained areas in the Krajeński Landscape Park include peatlands and wetlands in the valleys of smaller watercourses, such as the Kamionka and Sępolenka rivers. In many locations, a network of drainage ditches was constructed to enable effective groundwater removal, but at the same time, it significantly altered the natural hydrological cycle. Drainage activities were also carried out near lakes, where stream and ditch regulation changed lake recharge conditions. As a result, many lakes now receive less water, and some are being drained or disappearing altogether. Historical archival photographs (available in regional archives) frequently document the periodic clearing and deepening of these ditches, confirming the ongoing maintenance and operation of the drainage systems.

Drainage systems affected many aspects of the functioning of the hydrographic network and aquatic ecosystems in the Krajeński Landscape Park:

- Lowering of the groundwater table: Through drainage, water flows out of the area more quickly, leading to a drop in groundwater levels, even in areas not directly drained, due to hydrogeological connectivity. This negatively affects soil moisture conditions in natural habitats and the stability of natural water bodies.

- Reduction of landscape water retention: The loss of wetlands and peatlands, which act as natural water retention reservoirs, leads to faster runoff of precipitation, increasing the risk of summer droughts and spring floods.
- Acceleration of lake eutrophication: Water from drained wetlands and peatlands contains high levels of organic matter and dissolved carbon, which stimulate biogeochemical processes in lakes, accelerating eutrophication. The increased organic load also reduces water quality and alters the biological composition of aquatic ecosystems.
- Degradation of natural habitats: Wetlands and peatlands, which serve as important habitats for many plant and animal species, degrade and disappear as a result of drainage.

In the face of growing ecological and hydrological challenges, there is a gradual shift in the approach to drainage management. Increasing emphasis is now placed on restoring natural water conditions through: raising groundwater levels in peatland and wetland areas, constructing and upgrading weirs to enhance water retention, and rehabilitating former drainage ditches to serve ecological functions.

Such measures help mitigate eutrophication, improve landscape water retention, and support the recovery of natural habitats. Drainage operations in the Krajeński Landscape Park, particularly those carried out in the post II WW period, have had—and continue to have—a profound impact on the formation of the contemporary hydrographic network. While they brought significant benefits to agricultural production, their ecological and hydrological consequences are considerable and must be taken into account in nature conservation planning in the region. Integrating drainage management with environmental protection goals and implementing renaturalization processes now represents one of the main challenges for the sustainable development of the Krajeński Landscape Park.

CONCLUSIONS

The conducted research, based mainly on cartographic materials, clearly confirms that the transformations of the hydrographic network in the area of the Krajeński Landscape Park are largely the result of human activity on the environment. The intensive agricultural practices carried out since the mid-20th century and the development of water infrastructure have led to significant changes in the character and functioning of the river-lake system of the region.

Melioration works, being one of the main drivers of these transformations, were aimed at improving water conditions for agricultural use by lowering groundwater levels and draining wetlands. While these actions brought measurable economic benefits, they also resulted in the loss of natural water retention capacity and disturbances in the circulation of organic matter, contributing to the accelerated eutrophication of lakes and the degradation of wetland habitats.

The considerable reduction in the surface area of many lakes, resulting from both the natural succession of vegetation and the decline in groundwater levels, points to an escalating issue of hydrological changes that negatively affect biodiversity and weaken the ecological functions of these ecosystems. Additionally, climate change, such as rising temperatures and increasing variability of precipitation, exacerbates the negative anthropogenic effects, leading to further deterioration of hydrological and ecological conditions.

Projections indicate that without the implementation of appropriate conservation, the transformation processes of the hydrographic network will continue to intensify. The intensification of agriculture, further development of drainage infrastructure, and ongoing climate change may lead to a permanent lowering of groundwater levels, the loss of small lakes, and the further degradation of habitats. This, in turn, could result in reduced ecosystem resilience and the decline of natural retention functions, which are essential both for the local climate and for protection against droughts and floods.

In light of these challenges, it is crucial to implement sustainable water management, which incorporates the protection of water resources and the restoration of natural hydrological processes. Necessary measures include wetland restoration, rehabilitation of natural watercourses, limitation of environmentally harmful drainage, and the establishment of buffer zones to minimize the runoff of pollutants into waters. Furthermore, it is essential to conduct

systematic monitoring of hydrological and ecological changes and to undertake educational and informational initiatives targeted at local communities.

In conclusion, the protection and proper management of the hydrographic network of the Krajeński Landscape Park requires a holistic approach that balances environmental protection goals with economic needs. Only such actions will ensure the preservation of the uniqueness and functionality of the region's aquatic ecosystems, while securing their long-term sustainability and resilience to future environmental challenges.

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Трансформації гідрографічної мережі в постльодовикових областях на прикладі Краєнського ландшафтного парку

Круль Павел, Сжаттен Давід

Природоохоронні території є надзвичайною унікальною частиною природного середовища, яка потребує сталого управління, спрямованого на збереження її цінностей для майбутніх поколінь. Однак через вплив людської діяльності та кліматичні зміни фіксується низка змін, зокрема трансформації гідрографічної мережі.

Метою дослідження було оцінити ступінь трансформації гідрографічної мережі на прикладі Краєнського ландшафтного парку (північна Польща).

Через озерний характер досліджуваної території це середовище надзвичайно чутливе до будь-яких змін у водному господарстві. Аналізи, проведені на основі ГІС-інструментів, дозволили визначити основні напрямки трансформацій гідрографічної мережі за останні століття, демонструючи сильний тиск людської діяльності на ці зміни. Було відзначено зменшення поверхні озера, водночас збільшилася довжина річок та водовідвідних каналів. Ця тенденція відображала сильний дренаж, що здійснювався на цій території в минулому, антропогенні трансформації русел річок і прискорення процесу евтрофікації озер та водно-болотних угідь через зміни всієї гідрографічної мережі території.

Продемонстровано необхідність сталого управління територією ландшафтного парку з метою захисту водних середовищ та територій, пов'язаних з водою.

Ключові слова: *гідрографічна мережа, річки, озера, водно-болотні угіддя, ГІС, заповідні території, Краєнський ландшафтний парк*

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